Rainfall redistribution in subtropical Chinese forests changes over 22 years

Wanjun Zhang[1,2,3], Thomas Scholten[3], Steffen Seitz[3], Qianmei Zhang[1], Guowei Chu[1], Linhua Wang[1], Xin Xiong[4], Juxiu Liu[1]

[1]Key Laboratory of Vegetation Restoration and Management of Degraded Ecosystems, South China Botanical Garden, Chinese Academy of Sciences, Guangzhou, 510650, China

[2]Key Laboratory of Urban Water Safety Discharge and Resource Utilization, Hunan University of Technology, Zhuzhou, 412007, China

[3]Soil Science and Geomorphology, Department of Geosciences, University of Tübingen, Tübingen, 72070, Germany

[4]Jiangxi Provincial Key Laboratory of Carbon Neutrality and Ecosystem Carbon Sink，Lushan Botanical Garden, Jiangxi Province and Chinese Academy of Sciences, Jiujiang, 332900, China

Correspondence: Juxiu Liu (ljxiu@scbg.ac.cn) and Xin Xiong (xiongx@lsbg.cn)

Abstract

Rainfall redistribution through the vegetation canopy plays a key role in the hydrological cycle. Although there have been studies on the heterogeneous patterns of rainfall redistribution in some ecosystems, the understanding of this process in different stages of forest succession remains insufficient. Therefore, this study investigated the change tendency of rainfall redistribution and rainwater chemistry in a subtropical forest succession in South China, based on 22 years (2001–2022) of monitoring rainfall (740 valid events).

Results showed that at the event scale both throughfall ratio and stemflow ratio in pine forest (PF) were higher than in mixed forest (MF) and broadleaf forest (BF). At the interannual scale, throughfall and stemflow of forests experienced an initial decrease followed by a subsequent increase over the entire measurement period (except stemflow of the pine forest), which reflects the trend of open rainfall. The variability of throughfall showed an increase from MF to PF to BF, and the variability of stemflow likewise showed an increase from MF to PF to BF. Changes of throughfall and stemflow in the broadleaf forest are thus higher than those in the mixed forest and pine forest over time. Furthermore, important differences in rainwater chemistry fluxes among the three forest types were found, changing in varying order over time. On average, total nitrogen (TN) and total phosphorus (TP) fluxes of throughfall increased from BF to MF to PF, while the potassium (K^+) flux of throughfall showed a decrease from BF to MF to PF. Stemflow chemical fluxes varied less among forest types and over time, though tree species most importantly affected varying stemflow chemistry.

These results show important changes in patterns of rainfall redistribution over time and that characteristic variations are driven by rainfall and forest factors. This study thus provides insight into long-term rainfall redistribution processes by linking changes in rainfall spectra with a typical subtropical forest succession sequence.

Keywords: throughfall, stemflow, forest types, forest meteorology, long-term study

1 Introduction

In recent years, there has been on-going concern about the potential impacts of climate change on forest ecosystems, particularly regarding rainfall input to water resources (Reynaert et al., 2020; Grossiord et al., 2017; Bruijnzeel et al., 2011; Leuzinger and Körner, 2010). Numerous studies have documented rainfall regimes and their effect on the water cycle in different regions of the world, including spatial and temporal changes in the amount, intensity, and frequency (Brasil et al., 2018; Ponette-González et al., 2010). Meanwhile, these variables in rainfall refer to the redistribution of rainfall into canopy interception, throughfall and stemflow, being important components of hydrological processes in terrestrial ecosystems (Germer et al., 2010; Levia and Frost, 2006; Loustau et al., 1992). Rainfall redistribution patterns can impact biogeochemical cycles down to soil moisture distribution, which in turn affects the activity of soil microorganisms that decompose organic matter (Tonello et al., 2021a; Junior et al., 2017; Van Stan II and Pypker, 2015). For example, Sun et al. (2023) showed that throughfall reduction significantly affects the soil carbon cycle in a subtropical forest. Therefore, understanding the roles of rainfall redistribution in woodlands is essential.

Rainfall redistribution, as the partitioning into interception loss, throughfall and stemflow, is an important hydrological process that regulates water and nutrient cycling in forest ecosystems. Interception loss refers to the part of the event rainfall intercepted by the canopy, accounting for about 10%–30% of gross rainfall depending on the studied forest canopy, e.g. shrub (Zhang et al., 2015), mixed broadleaf (Yan et al., 2003), or pine (Loustau et al., 1992). The remaining rainwater reaches the ground either as throughfall or stemflow. Throughfall is a critical component of rainfall redistribution, and it contributes on average to approximately 60%–90% of the gross rainfall on the floor in forests, shrubland, or cropland. (Zhang et al., 2023; Zhang et al., 2021; Brauman et al., 2010; Marin et al., 2000). Raindrops coalesce or splash on canopy leaf surfaces, generating spatially different throughfall volume and raindrop kinetic energies which can be larger or lower than that of open rainfall (Levia et al., 2019; Goebes et al., 2015). Stemflow, the water flowing bottomwards along the plant stem or trunk, often accounts for only a small proportion (0–12%) of rainfall (Niu et al., 2023; Yue et al, 2021; Llorens and Domingo 2007). Nevertheless, stemflow inputs can be important as hot spots for near-trunk soils, inducing water and nutrient enrichment and deep infiltration, but also erosion (Zhao et al., 2023; Llorens et al., 2022). It can funnel more water than open rainfall on an equivalent area and contributes to 10% of the annual soil water input (Levia and Germer, 2015; Chang and Matzner, 2000). Throughfall and stemflow restrict water input to the soil layer, thereby affecting soil moisture conditions, runoff generation and water and nutrient cycling (Lian et al., 2022; Lacombe et al., 2018; Klos et al., 2014).

The proportions of rainfall redistribution are generally driven by meteorological conditions (e.g., rainfall amount, intensity, duration) and vegetation cover (e.g., canopy structures, tree characteristics) (Tonello et al., 2021a; Sun et al., 2018; Mużyło et al., 2012; Nanko et al., 2006). For meteorological conditions, numerous studies have documented that throughfall volume and stemflow volume increase with increasing gross rainfall and intensity (Ji et al., 2023; André et al., 2011). The ratios of throughfall and stemflow were both characterized as logarithmically increasing with rainfall, tending to be quasi-constant for heavy rainfall events (Zhang et al., 2021; Liu et al., 2019). This is also synchronously related to the gradual saturation of the canopy which limits the ratios of rainwater partitioning (Carlyle-Moses et al., 2004). Besides, differences in water volume spatially exist from place to place. The spatial variability (expressed as a coefficient of variation) of throughfall volume is generally higher for small rainfall events (< 10 mm) than for heavy rainfall events (Germer et al., 2006; Price et al., 1997).

Rainfall redistribution among different plant species can vary significantly due to differences in the structure and characteristics of their canopies. Specifically, key factors determining the redistribution of rainfall such as leaf area index (LAI), leaf shapes and orientations can affect the amount of intercepted loss and throughfall (Zhang et al., 2021; Goebes et al., 2015; Keim et al., 2006). The diameter at breast height (DBH), bark type and orientation of trunks/stems and branches influence the amount of stemflow (Levia et al., 2015; Livesley et al., 2014; Germer et al., 2010). For each of the rainfall partitioning fluxes, their responses to the influential predictors often show high variation. A modelling study of rainfall partitioning in China explained that throughfall was best represented by mean tilt angle (MTA), followed by DBH. Subsequently, DBH was the dominant predictor for stemflow, followed by LAI and bark texture (Zhang et al., 2023). Due to these factors, rainfall redistribution presented different degrees of spatial variability. This variability (expressed as coefficient of variation) decreased with increasing rainfall amount and intensity, consequently tending to be quasi-constant (Germer et al., 2006). Besides, at interannual scale, ratios of rainfall redistribution are driven by annual canopy structures. The study of Niu et al. (2023) documented that the annual throughfall ratio gradually increased, while the annual stemflow ratio and interception loss ratio decreased with increasing thinning intensity in shrub plantations. Meanwhile, annual changes of rainfall events (amount and intensity) reinforced the time instability of throughfall spatial variability (Rodrigues et al., 2022). Overall, the rainfall-canopy interactions play a key role in rainfall redistribution processes and further affect the water cycle in many ecosystems.

The vegetation canopy is the functional interface between an ecosystem and atmospheric wet deposition (Van Stan II and Pypker, 2015). Leaves and trunks/stems, acting as a filter, alter rainwater chemical concentrations via leaching and depositing processes. As a result, throughfall and stemflow exhibit high chemical concentrations compared to open rainfall (Jiang et al., 2021; Zimmermann et al., 2007). For instance, in a Chinese pine plantation, the volume-weighted mean concentrations of $NH4^{+}$ and $NO3^{-}$ in throughfall were significantly higher than those in open rainfall (Wang et al., 2023). Stemflow ion fluxes (e.g., K^{+}) from deciduous tree species were higher than those for evergreen tree species because of the differences in bark morphology and branch architecture (Su et al., 2019). Moreover, it is also common that throughfall and stemflow chemistry show fluctuating seasonality with the shifts in rainfall regime and leaf growth (Turpault et al., 2021; Siegert and Levia, 2014; Staelens et al., 2007). Plants mainly require N, P, K, Ca and Mg. In general, N, K and Ca are the most important inputs to a forest ecosystem, and P is the least. Phosphorus (P) is considered to be a limiting nutrient element in tropical and subtropical forests. The long-term productivity of vegetation depends on the input of atmospheric P. Besides, an increasing trend of atmospheric nitrogen (N) deposition with more frequent seasonal droughts in subtropical areas of China was reported (Zhou et al., 2011), and may inhibit the growth of plants and affect the productivity and functioning of forest ecosystems (Wu et al., 2023; Borghetti et al., 2017). Therefore, the important significance of atmospheric precipitation to an ecosystem can also be confirmed for element cycling, and canopy leaching plays an important role in the chemical cycle of forest ecosystems.

Although there have been studies on the spatiotemporal variability of rainfall redistribution, most of these are limited to data from short-term monitoring over several months to one-two years (Liu et al., 2019; Ziegler et al., 2009; Carlyle-Moses, 2004; Marin et al., 2000). There are few studies exceeding several years of measurements and simultaneously focusing on forest structural changes and rainwater interception

(Grunicke et al., 2020; Shinohara et al., 2015; Jackson, 2000). Long-term field monitoring studies are valuable to gain insight into the temporal dynamics of forest hydrological processes (Rodrigues et al., 2022; Sun et al., 2023; Levia and Frost, 2006). Such studies can also contribute to identifying patterns and trends in rainfall redistribution, which is essential for predicting the long-term effect of water resource change on forest ecosystems.

Therefore, in this study, we focus on the changing characteristics of throughfall and stemflow in a subtropical forest succession sequence (pine forest→mixed forest→ monsoon evergreen broadleaf forest), based on long-term monitoring. Specifically, the objectives are to analyze: (1) the changes in water volume of throughfall and stemflow, and (2) the changes in water chemistry (N, P, K^+) of rainfall, throughfall and stemflow among the three forests. We hypothesize that: (1) both throughfall and stemflow in the broadleaf forest are characterized by high variability compared to mixed forest and followed by pine forest, and (2) the chemical fluxes of throughfall and stemflow change over time from broadleaf forest to mixed forest to pine forest. We aim to assess the variability of forest hydrological processes from a long-term perspective to help predict future dynamic trends of water resources in subtropical forest ecosystems.

2 Materials and methods

2.1 Study site

This study was conducted at the Dinghushan Biosphere Reserve (23°09′ 21″ N ~ 23°11′ 30″ N, 112°30′ 39″ E ~ 112°33′ 41″ E) located in Zhaoqing City, South China. Dinghushan catchment consists of two streams both with 12 km length, which flow into the West River (the main trunk of the Pearl River). According to the Köppen-Geiger climate classification (Kottek et al., 2006), the study area belongs to tropical monsoon climate (Cwa) with pronounced wet (April-September) and dry season (October-March). The average annual temperature is 20.9 °C, and the annual rainfall and evaporation are 1900 mm and 1115 mm, respectively. Dinghushan Biosphere Reserve is covered with a complete horizontal succession series of three types of subtropical forest, which is highly representative of the region (Zhou et al., 2011). Monsoon evergreen broadleaf forest (BF) is 400 years old with typical tree species including *Castanopsis chinensis (Spreng.) Hance*, *Schima superba Gardner & Champ.*, *Cryptocarya concinna Hance*, etc. The mixed pine/broadleaf forest (MF) is a natural succession with a coniferous broadleaf ratio of about 4:6, and 70–80 years old. The main broadleaf tree species are *Schima superba Gardner & Champ*., *Castanopsis chinensis (Spreng.) Hance*, and the coniferous species *Pinus massoniana Lamb*. The pine forest (PF) planted before 1960 belongs to the primary succession community where *Pinus massoniana Lamb* forms the only tree layer. The community composition and biodiversity are shown in Table S1.

2.2 Gross rainfall, throughfall and stemflow monitoring

Atmospheric rainfall data was collected at Dinghushan Automatic Meteorological Station from 2001–2022. Automatic meteorological systems were used to measure atmospheric pressure (DPA501 gas-pressure meter), temperature (HMP45D sensor), relative humidity (HMP45D sensor), rainfall (SM1-1 pluviometer) and recorded with CR1000X datalogger (America Campbell). The resolution of data recording was ±0.2 mm with a time interval of 10 min. The raw data comprised annual rainfall amounts, as well as single rainfall events with throughfall and stemflow measurements.

Throughfall and stemflow were collected in all three forest types and synchronously measured. Devices with cross-shaped collectors (1.25 m^2) attached to reservoirs (1000 L) at the bottom were used to collect throughfall. Three throughfall devices were randomly installed in each forest field (Fig. S1).

Half-shell plastic tubes were installed around tree trunks attached to reservoirs (1000 L) at the bottom to collect stemflow. The ratio of volume (mL) to canopy area (cm^2) is the stemflow (mm). A total of 24 trees were selected to measure stemflow volume (Table S2). In detail, four tree species were selected in the broadleaf forest, including *Acmena acuminatissima* (Blume) Merr. et Perry (SF1), *Cryptocarya chinensis* (Hance) Hemsl. (SF2), *Gironniera subaequalis* Planch. (SF3), *Schima superba* Gardn. et Champ. (SF4), with 3 repetitions respectively. Three tree species were selected in the mixed forest, including *Castanea henryi* (Skam) Rehd. et Wils. (SF5), *Schima superba* Gardn. et Champ. (SF6), *Pinus massoniana* Lamb. (SF7), with 3 repetitions respectively. In the pine forest, *Pinus massoniana* Lamb. (SF8) was selected as the monitoring subject with 3 repetitions.

2.3 Rainwater chemistry measurement

For the measurement of rainwater chemistry, rainwater samples were taken in 2000, 2010 and 2022. The samples of open rainfall, throughfall and stemflow were manually collected for every one-month period, respectively. The samples of open rainfall and throughfall were collected with three repetitions, and stemflow with four repetitions in the broadleaf forest, three repetitions in the mixed forest and three repetitions in the pine forest. In total, 792 rainwater samples (108 open rainfall, 324 throughfall and 360 stemflow) were collected.

Rainwater samples were defrosted and filtered through 0.45 μm polypropylene membranes. Concentrations of total nitrogen (TN) and total phosphorus (TP) were measured using an ultraviolet spectrophotometer (Lambda 25, Perkin-Elmer), and ion potassium (K^+) was measured using an inductively coupled plasma optical emission spectrometer (Optima 2000, Perkin-Elmer). The original data of TN, TP and K^+ were processed into annual flux and monthly values with the weighted average method:

$$C = \frac{\Sigma C_i * V_i}{\Sigma V_i} \tag{1}$$

where C_i and V_i are the concentrations of ions (mg L^{-1}) and water sample volume (L) in each rainfall event, respectively.

2.4 Other measurement and statistical analysis

In the forests, plant density and canopy structure were measured every five years since 2000. In total, 25 plots of 20 m × 20 m (A1-A25 plots) were built on an area of 1ha to survey tree density (Fig. S1). Then, 25 plots of 5 m × 5 m (B1-B25 plots) were randomly set on the A1-A25 plots to survey shrub density. Finally, 25 plots of 1 m × 1 m (C1-C25 plots) were randomly set on the B1-B25 plots to survey herb density. The percentage of the surface area covered by plants to the total plot area is termed canopy coverage (%). 25 observation plots (1 m × 1 m) were selected in the 1 hm^2 area of each forest type. LAI (Leaf area index) was measured using a LAI-2200 plant canopy analyzer with 90° view caps (Li-Cor Inc., USA). 10 observation points (distance of about 10 m) were selected in the 1 hm^2 area of each forest type with 5 replications. Growth indicators of the selected trees have been recorded: tree height (m), diameter at breast height (DBH, cm), and crown area (CA, m^2). Tree height was measured using a laser range finder. A tape measure was used to measure the diameter of trees at a height of 1.3 m, namely DBH. CA: the laser rangefinder was used to measure the maximum diameter at the edge of the canopy, with multiple measurements at different points to ensure accuracy.

The differences in throughfall and stemflow among different forests were assessed using analysis of variance (ANOVA), followed by a Tukey test for multiple comparisons between means. Mann-Kendall (MK) test was used to analyze the variation trend of annual rainfall. All statistical procedures were conducted with α = 0.05 threshold for significance, in the IBM SPSS statistics 22.0 software (IBM Inc.).

3 Results

3.1 Rainfall and temperature characteristics

Based on the 22-year rainfall dataset from the Dinghushan area, annual gross rainfall ranged between 1370.0 and 2361.1 mm (Fig. 1). 78.0% of gross rainfall appeared in the wet season (April–September). The M-K test showed that rainfall was significantly decreasing trend from 2001–2007 (UF < 0, $P < 0.05$), and shifted into a significantly increasing pattern from 2012–2022 (UF > 0, $P < 0.05$). Moreover, 2008 and 2011 (the intersection of UF and UB) were the mutation time steps of the rainfall trend ($P < 0.05$). Anomalies were revealed in the temporal variability (coefficient of variation, *CV* of 16.6%) in annual rainfall (Fig. 1a). Anomalies varied at -426.4–476.8 mm and -258.0–471.4 mm in the wet season and dry season, respectively. By comparison, the dry season experienced greater variation with *CV* of 40.4% than the wet season with a *CV* of 21.7%. Besides, annual rain days tended to decrease over time from 2012 to 2021(Fig. 1b). Based on five rainfall classifications, it was shown among 22 years that rainfall <10 mm accounts for about 68.5% of total rain days (2856), while rainfall >50 mm account for about 4.9%. Besides, annual temperature changed between 21.8 °C and 23.3 °C over 22 years. The M-K test showed a statistically significant increase in temperature for 8 years out of 22 years (UF > 0, $P < 0.05$). Moreover, 2005 and 2013–2014 were the mutation time steps of the temperature trend ($P < 0.05$).

3.2 Variability of throughfall

Rainfall redistribution (throughfall and stemflow) among the three forests all experienced differing magnitudes for 22 years (Fig. 2). Annual throughfall was concentrated between 954.2 mm and 2192.6 mm. The M-K test showed that throughfall was in a significantly decreasing trend at first (UF < 0, $P < 0.05$) and then shifted into a significant increase (UF > 0, $P < 0.05$) from 2001–2022, similar to the trend of open rainfall. Differently, a mutation time step of throughfall occurred in 2008, 2011 and

2021 in the broadleaf forest, 2008 and 2011 in the mixed forest, 2006, 2008, 2011, and 2021 in the pine forest (P < 0.05). The throughfall ratio varied significantly both at event and interannual scales (Fig. 3a, b and c). The median annual throughfall ratio in the broadleaf forest varied between 60% and 120% with a CV of 16.4% from 2001–2022. The median throughfall ratio in the mixed pine and broadleaf forest varied between 80% and 110% with a CV of 9.7%. The median throughfall ratio in the pine forest varied between 59% and 110% with a CV of 11.8%. Therefore, the throughfall ratio was characterized by a low variability over an annual-time scale (CV < 20%). Besides, some differences in throughfall ratio were found among the three forest types based on rainfall classifications (Fig. 3d). For rainfall events <10 mm, the throughfall ratio range in the broadleaf forest was 30%–70%, while in the other two forest types, it was 15%–85%. The mean value of the throughfall ratio was small in the broadleaf forest (53.9%), though no significant differences among the three forests (P > 0.05) were detected. For rainfall events <50 mm, no significant difference in throughfall ratio among the three forest types was found (P > 0.05). However, the median values of the throughfall ratio in the pine forest (90.0%) and the mixed forest (89.4%) were both significantly larger than that in the broadleaf forest (83.7%) for rainfall events >50 mm.

CV values of throughfall based on all the rainfall event classifications were drawn in the Fig. 4a. Results showed that the median CV of throughfall in the pine forest (15.2%) was lower than that for the broadleaf forest (21.7%) and for the mixed forest (26.3%) for rainfall events <10 mm. For rainfall events >10 mm, small differences in median CV among the three forest types were shown. Meanwhile, CV values decreased with the increasing rainfall events, eventually falling to 3.5%–4.3%. Besides, CV values of throughfall based on the interannual scale were drawn in the Fig. 5a, b and c. Annual CV values among different forest types showed different fluctuations over time. The medians of CV in annual, wet and dry seasons presented different orders in different years. According to linear fitting, significant negative correlations were found in the median of CV_{TF} in the mixed forest over time (r = 0.63, P < 0.01). In addition, the fitted result of in total 740 rainfall events in 22 years showed that CV values of throughfall significantly decreased with increasing gross rainfall (Fig. S2).

3.3 Variability of stemflow

Annual stemflow was concentrated between 9.0 and 119.7 mm over 22 years (Fig. 2). More stemflow was collected in the broadleaf forest and mixed forest than in the pine forest. The M-K test showed that stemflow of both broadleaf forest and mixed forest was decreasing at first ($UF < 0$, $P < 0.05$) and then shifted into an increase ($UF > 0$, $P < 0.05$), different from the continuously increasing trend of pine forest ($UF > 0$). The mutation time steps of stemflow occurred in 2008 in the broadleaf forest, 2011 in the mixed forest, 2006, 2012 and 2015 in the pine forest ($P < 0.05$). Stemflow ratio changed significantly both at the event and interannual scales (Fig. 3a, b and c). For 22 years, the median annual stemflow ratio in the broadleaf forest varied between 1.3% and 5.4% with a *CV* of 56.2%. The stemflow ratio of mixed forest varied between 1.5% and 4.4% with a *CV* of 38.6%. In the pine forest, it varied between 0.3% and 1% with a *CV* of 50.9%. This indicated that the stemflow ratio was characterized by an extremely high variability over time. Similar to the seasonal throughfall ratio, the medians of stemflow ratios in annual, wet and dry seasons presented different orders in different years. Besides, the stemflow ratio significantly changed among tree species and rainfall classifications (Fig. 3e). By comparison, the stemflow ratios of the SF1 and SF2 trees in the broadleaf forest were both higher in all the tree species for the rainfall events <50 mm. However, for strong events (>50 mm), the stemflow ratio of the SF5 tree in the mixed forest was highest for all tree species, followed by the trees in the broadleaf forest. For all the rainfall events, the stemflow ratio of SF7 in the mixed forest and SF8 in the pine forest were both lower than that for other tree species.

CV values of stemflow based on rainfall event classifications were drawn in Fig. 4b. By comparison, stemflow varied more than throughfall across all rainfall events, with CV_{SF} values of 25%–130%. Median *CV* of stemflow in the pine forest was always lower (45%–68%) than that for the other two forest types (56%–120%). *CV* values of stemflow based on an interannual scale changed over time among different forest types (Fig. 5d, e and f). The medians of CV_{SF} in annual, wet and dry seasons presented different orders in different years. By comparison, CV_{SF} was always greater than CV_{TF}, and the interannual fluctuation of CV_{SF} was also stronger than CV_{TF}. According to linear fitting, significant negative correlations were found in the median of CV_{SF} in the broadleaf forest over time ($r = 0.73$, $P < 0.001$)). In addition, the fitted result of in total 740 rainfall events in 22 years showed that *CV* values of stemflow both significantly decreased with increasing gross rainfall (Fig. S2).

3.4 Rainwater chemistry

Rainwater (open rainfall, throughfall and stemflow) chemical properties (TN, TP and K^+ concentration) were measured in the three forest types, respectively. All of TN, TP and K^+ values are presented in the order stemflow > throughfall > open rainfall (Fig. 6a, b and c). However, changes of TN, TP and K^+ were different for the three forest types in 2000, 2010, and 2022. For instance, in 2000 and 2010, TN values of throughfall and stemflow decreased for both from pine forest to mixed forest to broadleaf forest, while no such result could be confirmed in 2022. Similarly, TP values of throughfall in the broadleaf forest were 1.3 times higher than in the pine forest in 2022, while TP values in the pine forest were 6.8 times higher than that in the broadleaf forest in 2000. K^+ values of stemflow in 2010 (6.76 mg L^{-1}) and 2022 (6.22 mg L^{-1}) were higher for the broadleaf forest than for the pine forest (3.76 mg L^{-1} and 2.46 mg L^{-1}), which was different from that in 2022.

TN, TP and K^+ fluxes of stemflow were $<$ 10 kg ha^{-1} a^{-1}, 0.2 kg ha^{-1} a^{-1}, 6 kg ha^{-1} a^{-1}, respectively, and all lower than those of throughfall and open rainfall (Fig. 7d, e and f). In 2000, 2010, and 2022, TN fluxes (39.4–87.4 kg ha^{-1} a^{-1}) were 1.2–1.8 times higher than that of open rainfall, 3.3–28.0 times higher than that of stemflow. TP fluxes (1.1–2.7 kg ha^{-1} a^{-1}) were 1.0–2.3 times higher than that of open rainfall, 8.7–31.4 times higher than that of stemflow. K^+ flux (21.5–59.2 kg ha^{-1} a^{-1}) was 2.2–8.1 times higher than that of open rainfall, 2.2–26.8 times greater than that of stemflow. In addition, TN, TP and K^+ fluxes of stemflow increased with succession from primary to climax, namely pine forest<mixed forest<broadleaf forest. Different from this, differences in chemical fluxes of throughfall were not found among different forests, nor among different periods.

Moreover, monthly chemical concentrations in rainfall, throughfall and stemflow showed distinct changes (Fig. 7). Monthly TN, TP and K^+ concentrations of rainfall were always lower than those of stemflow for all trees. Monthly TN, TP and K^+ of stemflow in the dry season were generally higher than in the wet season. High monthly TN concentrations of stemflow with SF6 of mixed forest and SF8 of pine forest were found, especially in the dry season with maximum TN concentrations of 27.59 mg L^{-1} at SF6 and 19.94 mg L^{-1} at SF8, respectively. Differently, a high monthly K^+ concentration of stemflow at SF4 in broadleaf forest was found, with a maximum K^+ concentration of 25.17 mg L^{-1} in the dry season.

4 Discussion

4.1 Open rainfall partitioned to throughfall and stemflow

Studies in forests have confirmed that throughfall volume increased with increasing gross rainfall at the event scale, accounting for 60%–80% of gross rainfall (Ji et al., 2023; André et al., 2011; Carlyle-Moses, 2004). Throughfall ratio changed over time and showed different fluctuations among different forests (Fig. 3). During light rainfall events with rainfall amounts <10 mm, a low proportion of raindrops would reach the ground as throughfall, as the tree canopy intercepts almost all the incoming raindrops. Specifically, high canopy coverage in broadleaf forests can reinforce raindrop intercept (Brasil et al., 2018; Ponette-González et al., 2010), consequently generating a lower throughfall ratio than those in the mixed forest and pine forest (Fig. 3). During moderate rainfall events (10–50 mm), given that the intercept effect of the wetting tree canopy was weakened (Shinohara et al., 2015), throughfall ratio was in a high and steady state. As the gross rainfall increases further (>50 mm), significant differences of throughfall ratio were found among the three forests. The throughfall ratio was significantly lower in the broadleaf forest than those in the other two forests. Likewise, such differences due to the rainfall event class also appeared in other forest studies with stands formed by beech, pine in monocultures and mixed pine-beech (Blume et al., 2022). Influenced by forest stand characteristics, throughfall therefore indicated different forest water budgets.

Stemflow of forests was variably controlled by tree species, on average accounting for about <10% of gross rainfall, and partly even lower (<1%) (Sun et al., 2018; André et al., 2008; Crockford and Richardson, 1990). In our study site, the lowest stemflow (<1%) was collected in the pine forest, though weakly increasing with rainfall classifications (Fig. 3). Stemflow ratio in the broadleaf forest was maintained at 5%–10% without the effect of rainfall amount seemingly. In detail, stemflow ratio of pine forest (SF8) was significantly lower than those of broadleaf forest (SF1~4). In the mixed forest, broad-leaved trees (SF5 and SF6) have larger stemflow than pine trees (SF7). However, for some rainfall events, a particularly low proportion of stemflow in the broadleaf forest and an extraordinarily high proportion in the pine forest were caught. This implied the key role of rainfall conditions (e.g., intensity, duration) and tree species with tree traits (e.g., branch angle), consistent with reported studies e.g., in an evergreen forest (Chen et al., 2019; Bruijnzeel et al., 2011) and pine forest (Pinos et al., 2021; Crockford and Richardson, 1990). Moreover, ANOVA showed significant differences in stemflow ratio among tree species and rainfall classifications ($P < 0.001$) (Table 1). This indicated that rainfall and tree species simultaneously affect stemflow. Branch inclination angle, canopy cover, tree height and DBH of tree species proved to be key factors in stemflow yield (Levia et al., 2015).

Throughfall and stemflow were generally enriched in chemical concentration compared with open rainfall due to leachable canopy/stem ion pools (Jiang et al., 2021; Van Stan et al., 2017; Zimmermann et al., 2007). In our study, the concentration of K^+ in stemflow was 16 times higher than that in open rainfall and in throughfall reached up to 11 times higher than open rainfall (Fig. 6). Similar results were also found in forestry plantations (*Acacia mangium* and *Dimocarpus longan*) of South China (Shen et al., 2013), or in Oriental beech (*Fagus orientalis* Lipsky) trees in Northern Iran (Moslehi et al., 2019), indicating strong K^+ leaching from the canopy. Even so, throughfall was generally characterized by high fluxes compared to open rainfall followed by stemflow, it thus is the largest contributor to wet deposition. Meanwhile, the TN flux of throughfall was greatest in the pine forest in 2010, the TP flux of throughfall was greatest in the broadleaf forest in 2000, and the K^+ flux of throughfall was greatest in the mixed forest in 2010. It should be noted that the differences in rainwater chemistry shifted over time among the three forests. Accordingly, throughfall and stemflow via the canopy and stem to the soil are a significant contributor, and their long-term effect on ecosystems needs more scientific attention (Fan et al., 2021). After all, atmospheric wet deposition provides important nutrient amounts for ecosystems, but also imposes a considerable burden on the ecosystems in general. For instance, N enrichment and P limitation have proven to have different effects on soil carbon sequestration, microbial community composition and forest productivity, especially in tropical and subtropical forest ecosystems with highly weathered soils (Zheng et al., 2022; Li et al., 2016; Huang et al., 2012). Besides, throughfall and stemflow was mainly characterized by low chemical concentrations in the wet season and high concentrations in the dry season. Primary reasons for seasonal rainwater chemistry may be attributable to moisture source associated with frontal weather systems and gradually depleting effect with increasing rainfall amount (Dunkerley, 2014; Germer et al., 2007). The present study in subtropical forests and previous studies in tropical forests and European temperate forests all exhibited variable rainwater chemistry in throughfall and stemflow, both spatially and temporally (Zimmermann et al., 2007; Staelens et al., 2006; Seiler and Matzner, 1995). The chemical concentration of rainfall redistribution was also affected profoundly by canopy and stem parameters of tree species (Tonello et al., 2021b; Chen et al., 2019). In our study, some differences in TN, TP and K^+ were also found among SF1~SF8 due to tree-species-specific effects (Legout et al., 2016; De Schrijver et al., 2007).

4.2 Long-term changes in rainfall in forests

Rainfall regimes induce divergent spatially hydrological changes (Wu et al., 2024). Likewise, our study found that the throughfall of forests experienced a decrease followed by an increase from 2001–2022, similar to the trend of open rainfall, and stemflow showed characteristic trends in different forests especially in the pine forest (Fig. 1). This suggested that the complexity of forest structure and rainfall amount and their change exacerbated the spatio-temporal variability of throughfall and stemflow. Firstly, interannual variability of forest structure (e.g., canopy coverage, leaf area index) and tree parameters (e.g., height, DBH, and CA) made throughfall and stemflow distribution uncertain (Yue et al., 2021). From 2001 to 2022, changes in forest structure were confirmed in all three forests, such as changes in plant density, canopy coverage and LAI (Fig. 8). Throughfall ratio and stemflow ratio in the succession forest systems all varied over time accordingly. Similarly, driven by forest structure (e.g., tree density, species dominance), a six-year dataset from the Brazilian Atlantic Forest showed that the spatial variability of throughfall over time was less stable (Rodrigues et al., 2022). Besides, the variation of stemflow (CV_{SF}) was larger than that of throughfall (CV_{TF}) (Fig. 4), which probably was attributed to the differences of tree species in stemflow (Fig. 3). For a forest succession, a 17 years' study showed that the shift from monoculture Japanese red pine to mixture of red pine, evergreen oak and deciduous trees made stemflow significantly increasing (Iida et al., 2005). Likewise, for the forest succession in Dinghushan area, stemflow ratio in the broadleaf forest and mixed forest were both higher than that in the tree-monospecific pine forest. High plant density (tree and shrub) and LAI in broadleaf forest and mixed forest conduce to rainwater interception of multi-canopy trees through more leaves and angled branches, which potentially enhanced stemflow (Fig. 8). Indeed, some differences of rainfall redistribution appeared in multi-layered vegetative structure. An experiment on vegetation communities with a complex multi-layered structure found that interception loss from shrubs was two times higher than from trees, and smaller trees generated stemflow more efficiently than the higher ones (Exler and Moore, 2022). Based on the 22 years' data from the forest community survey in our study site, forest canopy parameters (e.g., coverage and LAI) of trees and shrubs showed variation over time from 2001 to 2022 (Fig. 8). In the broadleaf forest, plant density of trees and canopy coverage of shrubs showed a slight increment compared to the other two forest types, though LAI was decreasing. During this period, interannual throughfall ratio and stemflow ratio showed significant change over time (Fig. 3), implying the role of interannual variation of forest structure in the rainfall redistribution process.

Secondly, ongoing rainfall changes with different magnitudes favor the different levels of rainfall redistribution over time (Lian et al., 2022). At the event scale, throughfall and stemflow proportions of forests were both low with rainfall events <10 mm. The variations of throughfall and stemflow were both larger for gross rainfall <10 mm than events >10 mm. Rainfall threshold associated with the canopy interception capacity had an impact on throughfall and stemflow generation (Zabret et al., 2018; André et al., 2008; Durocher, 1990). After the raindrop capacity of the canopy reached its peak, throughfall and stemflow were documented to match the gross rainfall. Therefore, low proportions and high spatial variability appeared before the rainfall threshold, and after that, relatively high proportions and low variability until a stable level were observed in the three forests. Moreover, at the interannual scale, the rain days in different magnitudes presented fluctuation over 22 years (Fig. 1). This fluctuation of rain days and its magnitude distribution potentially regulated the long-term changes of open rainfall partitioned to interception loss, throughfall and stemflow. Consequently, throughfall and stemflow, influenced by the comprehensive effect of rainfall regimes and forest structures, presented spatiotemporal variability at different levels (Fig. 3–6). From a long-term perspective, changes in rainfall redistribution potentially make forest water and biogeochemistry budgets more complex. Further knowledge of the long-term accumulative effect of rainfall redistribution on forest water and chemistry (e.g., soil and plant) is needed in the future.

Throughfall and stemflow are part of rainfall and are key players in the water cycle process. Based on the connection of the water cycle to precipitation and temperature and under the background of climate change, the frequency of extreme events (heavy rainfall, droughts) needs to be anticipated in the effect on rainfall redistribution and solute transport within forests, which in turn may affect the water cycle and biogeochemical cycles (Blume et al., 2022). In this study, it should be noted that the 2008 rainfall data can be used as an example of an extreme event. In 2008, extreme weather events occurred in South China. Freezing events occurred in the dry season, and continuous heavy rain and typhoon events occurred in the wet season. Gross rainfall was larger than in other years, with an annual rainfall of 2361.1 mm (22-year average annual rainfall of 1848.6 mm) (Fig. 1). At the same time, a total of 26 throughfall events were collected in 2008. The throughfall and stemflow trend of different forests presented different degrees of disturbance under the background of mutation of open rainfall (Fig. 2). In this process, the driving effect of forest structure and rainfall on throughfall and stemflow mutation is synchronous. More data and modeling are needed to support the relevant study about the effect of climate change on rainfall redistribution in the future.

5 Conclusions

The current study investigated long-term changing characteristics of rainfall redistribution along a subtropical forest succession sequence with pine forest (PF), mixed pine and broadleaf forest (MF), and monsoon evergreen broadleaf forest (BF). Firstly, in the 740 measured rainfall events, the throughfall ratio changed from BF < MF < PF, and the stemflow ratio changed from BF > MF > PF. The variation of stemflow was higher (CV >50%) than that of throughfall (CV <25%). Secondly, throughfall and stemflow of the investigated forests experienced a decrease followed by an increase from 2001–2022 (except stemflow of the pine forest), similar to the trend of open rainfall. Driven by rainfall and forest factors, the interannual variability of both throughfall and stemflow in the broadleaf forest was higher than those in the mixed forest and pine forest, which was different from that of annual open rainfall.

For rainwater chemistry, differences in the element fluxes in throughfall and stemflow among the three forest types were confirmed based on data from 2001, 2010, and 2022. On average, TN and TP fluxes of throughfall developed from BF < MF < PF, while K^+ flux of throughfall changed from BF > MF > PF. Over time, rainwater chemical concentrations were lower in the wet season than in the dry season. Given the smaller proportion of open rainfall, stemflow chemical fluxes varied less among forest types and over time, though tree species exactly represented the differences in stemflow chemistry. Nevertheless, its funnel effect on soil and plants over time still deserves more scientific attention in the future.

The above results indicate that the water volume and chemistry of rainfall during redistribution processes under forests represent not the same trend as open rainfall over time, and throughfall and stemflow depend on the effect of rainfall and forest factors. This study thus provides insight into the rainfall redistribution process by linking the long-term change of rainfall patterns with a subtropical forest succession sequence.

Code and data availability. The data used to derive to the conclusions of the present study are freely accessible. All the data were obtained from the CNERN dataset (http://dhf.cern.ac.cn/meta/metaData).

Author contributions. WJZ: conceptualization, investigation, data analysis, writing, visualization. TS and SS: reviewing, supervision. QMZ and GWC: resources, data curation, LHW: reviewing, JXL and XX: reviewing, funding acquisition, supervision

Competing interests. The authors declare that they have no conflict of interest.

Disclaimer. Publisher's note: Copernicus Publications remains neutral with regard to jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors.

Acknowledgements. Wanjun Zhang would like to acknowledge the financial support from the CSC Fellowship.

Financial support. This research has been supported by The Key-Area Research and Development Program of Guangdong Province (Grant No. 2022B1111230001), the National Natural Science Foundation of China (Grant Nos. 42207158 and 32101342) and the China Postdoctoral Science Foundation (Grant Nos. 2021M703259, 2021 M703260, 2021M693220).

Review statement. This paper was edited by Loes van Schaik and reviewed by two anonymous referees.

References

André, F., Jonard, M., Jonard, F., and Ponette, Q.: Spatial and temporal patterns of throughfall volume in a deciduous mixed-species stand, J. Hydrol., 400(1–2), 244–254, https://doi.org/10.1016/j.jhydrol.2011.01.037, 2011.

André, F., Jonard, M., and Ponette, Q.: Influence of species and rain event characteristics on stemflow volume in a temperate mixed oak–beech stand, Hydrol. Process., 22(22), 4455–4466, https://doi.org/10.1002/hyp.7048, 2008.

Blume, T., Schneider, L., and Güntner, A.: Comparative analysis of throughfall observations in six different forest stands: Influence of seasons, rainfall-and stand characteristics, Hydrol. Process., 36(3), e14461, https://doi.org/10.1002/hyp.14461, 2022.

Borghetti, M., Gentilesca, T., Leonardi, S., Van Noije, T., and Rita, A.: Long-term temporal relationships between environmental conditions and xylem functional traits: a meta-analysis across a range of woody species along climatic and nitrogen deposition gradients, Tree Physiol., 37(1), 4-17, https://doi.org/10.1093/treephys/tpw087, 2017.

Brasil, J.B., Andrade, E.M.d., Palácio, H.A.d.Q., Medeiros, P.H.A., and Santos, J.C.N.d.: Characteristics of precipitation and the process of interception in a seasonally dry tropical forest, J. Hydrol-Reg. Stud., 19, 307–317, https://doi.org/10.1016/j.ejrh.2018.10.006, 2018.

Brauman, K.A., Freyberg, D.L., and Daily, G.C.: Forest structure influences on rainfall partitioning and cloud interception: A comparison of native forest sites in Kona, Hawai'I, Agric. For. Meteorol., 150(2), 265–275, https://doi.org/10.1016/j.agrformet.2009.11.011, 2010.

Bruijnzeel, L.A., Mulligan, M., and Scatena, F.N.: Hydrometeorology of tropical montane cloud forests: emerging patterns, Hydrol. Process., 25(3), 465–498, https://doi.org/10.1002/hyp.7974, 2011.

Carlyle-Moses, D.E., Laureano, J.F., and Price, A.G.: Throughfall and throughfall spatial variability in Madrean oak forest communities of northeastern Mexico, J. Hydrol., 297(1–4), 124–135, https://doi.org/10.1016/j.jhydrol.2004.04.007, 2004.

Chen, S., Cao, R., Yoshitake, S., and Ohtsuka, T.: Stemflow hydrology and DOM flux in relation to tree size and rainfall event characteristics, Agric. For. Meteorol., 279, 107753, https://doi.org/10.1016/j.agrformet.2019.107753, 2019.

Crockford, R.H., and Richardson, D.P.: Partitioning of rainfall in a eucalypt forest and pine plantation in southeastern Australia: II Stemflow and factors affecting stemflow in a dry sclerophyll eucalypt forest and a Pinus radiata plantation, Hydrol. Process., 4(2), 145–155, https://doi.org/10.1002/hyp.3360040205, 1990.

De Schrijver, A., Geudens, G., Augusto, L., Staelens, J., Mertens, J., Wuyts, K., Gielis, L., and Verheyen, K.: The effect of forest type on throughfall deposition and seepage flux: a review, Oecologia, 153, 663-674, https://doi.org/10.1007/s00442-007-0776-1, 2007.

Dunkerley, D.: Stemflow on the woody parts of plants: dependence on rainfall intensity and event profile from laboratory simulations, Hydrol. Process., 28(22), 5469–5482, https://doi.org/10.1002/hyp.10050, 2014.

Durocher, M.G.: Monitoring spatial variability of forest interception, Hydrol. Process., 4(3), 215–229, https://doi.org/10.1002/hyp.3360040303, 1990.

Exler, J.L., and Moore, R.D.: Quantifying throughfall, stemflow and interception loss in five vegetation communities in a maritime raised bog, Agric. For. Meteorol., 327, 109202, https://doi.org/10.1016/j.agrformet.2022.109202, 2022.

Fan, Y.X., Lu, S.X., He, M., Yang, L.M., Hu, W.F., Yang, Z.J., Liu, X.F., Hui, D.F., Guo, J.F., and Yang, Y.S.: Long-term throughfall exclusion decreases soil organic phosphorus associated with reduced plant roots and soil microbial biomass in a subtropical forest, Geoderma, 404, 115309, https://doi.org/10.1016/j.geoderma.2021.115309, 2021.

Germer, S., Elsenbeer, H., and Moraes, J.M.: Throughfall and temporal trends of rainfall redistribution in an open tropical rainforest, south-western Amazonia (Rondônia, Brazil), Hydrol. Earth Syst. Sci, 10(3), 383–393, https://doi.org/10.5194/hess-10-383-2006, 2006.

Germer, S., Neill, C., Krusche, A.V., Neto, S.C.G., and Elsenbeer, H.: Seasonal and within-event dynamics of rainfall and throughfall chemistry in an open tropical rainforest in Rondônia, Brazil, Biogeochemistry, 86, 155–174, https://doi.org/10.1007/s10533-007-9152-9, 2007.

Germer, S., Werther, L., and Elsenbeer, H.: Have we underestimated stemflow? Lessons from an open tropical rainforest, J. Hydrol., 395(3-4), 169–179, https://doi.org/10.1016/j.jhydrol.2010.10.022, 2010.

Goebes, P., Bruelheide, H., Härdtle, W., Kröber, W., Kühn, P., Li, Y., Seitz, S., von Oheimb, G., and Scholten, T.: Species-specific effects on throughfall kinetic energy in subtropical forest plantations are related to leaf traits and tree architecture, PLoS one, 10(6), e0128084, https://doi.org/10.1371/journal.pone.0128084, 2015.

Grunicke, S., Queck, R., and Bernhofer, C.: Long-term investigation of forest canopy rainfall interception for a spruce stand, Agric. For. Meteorol., 292, 108125, https://doi.org/10.1016/j.agrformet.2020.108125, 2020.

Grossiord, C., Sevanto, S., Dawson, T. E., Adams, H.D., Collins, A.D., Dickman, L.T., Newman B.D., Stockton, E.A., and McDowell, N.G.: Warming combined with more extreme precipitation regimes modifies the water sources used by trees, New Phytol., 213(2), 584–596, https://doi.org/10.1111/nph.14192, 2017.

Huang, W.J., Zhou, G.Y., and Liu, J.X.: Nitrogen and phosphorus status and their influence on aboveground production under increasing nitrogen deposition in three successional forests, Acta Oecologica, 44, 20–27, https://doi.org/10.1016/j.actao.2011.06.005, 2012.

Iida, S.I., Tanaka, T., and Sugita, M.: Change of interception process due to the succession from Japanese red pine to evergreen oak, J. Hydrol., 315(1–4), 154–166, https://doi.org/10.1016/j.jhydrol.2005.03.024, 2005.

Jackson, N.A.: Measured and modelled rainfall interception loss from an agroforestry system in Kenya, Agric. For. Meteorol., 100, 323–336, https://doi.org/10.1016/S0168-1923(99)00145-8, 2000.

Ji, S.Y., Omar, S.I., Zhang, S.B, Wang, T.F, Chen, C.F, and Zhang, W.J.: Comprehensive evaluation of throughfall erosion in the banana plantation, Earth Surf. Proc. Land., 47(12), 2941–2949, https://doi.org/10.1002/esp.5435, 2022.

Jiang, Z.Y., Zhi, Q.Y., Van Stan, J.T., Zhang, S.Y., Xiao, Y.H., Chen, X.Y., and Wu, H.W.: Rainfall partitioning and associated chemical alteration in three subtropical urban tree species, J. Hydrol., 603, 127109, https://doi.org/10.1016/j.jhydrol.2021.127109, 2021.

Junior, J.J., Mello, C.R., Owens, P.R., Mello, J.M., Curi, N., and Alves, G.J.: Time-stability of soil water content (SWC) in an Atlantic Forest-Latosol site, Geoderma, 288, 64–78, https://doi.org/10.1016/j.geoderma.2016.10.034, 2017.

Keim, R.F., Tromp-van Meerveld, H.J., and McDonnell, J.J.: A virtual experiment on the effects of evaporation and intensity smoothing by canopy interception on subsurface stormflow generation, J. Hydrol., 327(3–4), 352–364, https://doi.org/10.1016/j.jhydrol.2005.11.024, 2006.

Klos, P.Z., Chain-Guadarrama, A., Link, T.E., Finegan, B., Vierling, L.A., and Chazdon, R.: Throughfall heterogeneity in tropical forested landscapes as a focal mechanism for deep percolation, J. Hydrol., 519, 2180–2188, https://doi.org/10.1016/j.jhydrol.2014.10.004, 2014.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., and Rubel, F.: World map of the Köppen-Geiger climate classification updated, Meteorol. Z., 15(3), 259–263, https://doi.org/10.1127/0941-2948/2006/0130, 2006.

Lacombe, G., Valentin, C., Sounyafong, P., De Rouw, A., Soulileuth, B., Silvera, N., Pierret, A., Sengtaheuanghoung, O., and Ribolzi, O.: Linking crop structure, throughfall, soil surface conditions, runoff and soil detachment: 10 land uses analyzed in Northern Laos, Sci. Total Environ., 616, 1330–1338, https://doi.org/10.1016/j.scitotenv.2017.10.185, 2018.

Legout, A., van Der Heijden, G., Jaffrain, J., Boudot, J. P., and Ranger, J.: Tree species effects on solution chemistry and major element fluxes: A case study in the Morvan (Breuil, France), Forest Ecol. Manag., 378, 244–258, https://doi.org/10.1016/j.foreco.2016.07.003, 2016.

Leuzinger, S., and Körner, C.: Rainfall distribution is the main driver of runoff under future CO_2-concentration in a temperate deciduous forest, Global Change Biol., 16(1), 246–254, https://doi.org/10.1111/j.1365-2486.2009.01937.x, 2010.

Levia, D. F., Nanko, K., Amasaki, H., Giambelluca, T. W., Hotta, N., Iida, S. I., Mudd, R.G., Nullet, M.A., Sakai, N., Shinori, Y., Sun X.C., Suzuki, M., Tanaka, N., Tantasirin, C., and Yamada, K.: Throughfall partitioning by trees, Hydrol. Process., 33(12), 1698–1708, https://doi.org/10.1002/hyp.13432, 2019.

Levia, D.F., and Germer, S.: A review of stemflow generation dynamics and stemflow-environment interactions in forests and shrublands, Rev. Geophys., 53(3), 673–714, https://doi.org/10.1002/2015RG000479, 2015.

Levia Jr, D.F., and Frost, E.E.: Variability of throughfall volume and solute inputs in wooded ecosystems, Prog. Phys. Geog., 30(5), 605–632, https://doi.org/10.1177/0309133306071145, 2006.

Li, Y., Niu, S.L, and Yu, G.R.: Aggravated phosphorus limitation on biomass production under increasing nitrogen loading: a meta-analysis, Global Change Biol., 22(2), 934–943, https://doi.org/10.1111/gcb.13125, 2016.

Lian, X., Zhao, W.L., and Gentine, P., 2022. Recent global decline in rainfall interception loss due to altered rainfall regimes. Nat. Commun. 13(1), 7642. https://doi.org/10.1038/s41467-022-35414-y

Liu, J.Q., Liu, W.J., Li, W.X., and Zeng, H.H.: How does a rubber plantation affect the spatial variability and temporal stability of throughfall?, Hydrol. Res., 50(1), 60–74, https://doi.org/10.2166/nh.2018.028, 2019.

Livesley, S.J., Baudinette, B., and Glover, D.: Rainfall interception and stem flow by eucalypt street trees – The impacts of canopy density and bark type, Urban For. Urban Gree., 13(1), 192–197, https://doi.org/10.1016/j.ufug.2013.09.001, 2014.

Llorens, P., and Domingo, F.: Rainfall partitioning by vegetation under Mediterranean conditions. A review of studies in Europe, J. Hydrol., 335(1–2), 37–54, https://doi.org/10.1016/j.jhydrol.2006.10.032, 2007.

Llorens, P., Latron, J., Carlyle-Moses, D.E., Näthe, K., Chang, J.L., Nanko, K., Lida, S., and Levia, D.F.: Stemflow infiltration areas into forest soils around American beech (*Fagus grandifolia* Ehrh.) trees, Ecohydrology, 15(2), e2369, https://doi.org/10.1002/eco.2369, 2022.

Loustau, D., Berbigier, P., and Granier, A.: Interception loss, throughfall and stemflow in a maritime pine stand. II. An application of Gash's analytical model of interception, J. Hydrol., 138(3–4), 469–485, https://doi.org/10.1016/0022-1694(92)90131-E, 1992.

Marin, C.T., Bouten, W., and Sevink, J.: Gross rainfall and its partitioning into throughfall, stemflow and evaporation of intercepted water in four forest ecosystems in western Amazonia, J. Hydrol., 237(1–2), 40–57, https://doi.org/10.1016/S0022-1694(00)00301-2, 2000.

Moslehi, M., Habashi, H., Khormali, F., Ahmadi, A., Brunner, I., and Zimmermann, S.: Base cation dynamics in rainfall, throughfall, litterflow and soil solution under Oriental beech (*Fagus orientalis* Lipsky) trees in northern Iran, Ann. Forest Sci., 76(2), 1–12, https://doi.org/10.1007/s13595-019-0837-8, 2019.

Mużyło, A., Llorens, P., and Domingo, F.: Rainfall partitioning in a deciduous forest plot in leafed and leafless periods, Ecohydrology, 5(6), 759–767, https://doi.org/10.1002/eco.266, 2012.

Nanko, K., Hotta, N., and Suzuki, M.: Evaluating the influence of canopy species and meteorological factors on throughfall drop size distribution, J. Hydrol., 329(3–4), 422–431, https://doi.org/10.1016/j.jhydrol.2006.02.036, 2006.

Niu, X.T., Fan, J., Du, M.G., Dai, Z.J., Luo, R.H., Yuan, H.Y., and Zhang, S.G.: Changes of Rainfall Partitioning and canopy interception modeling after progressive thinning in two shrub plantations on the Chinese Loess Plateau, J. Hydrol., 619, 129299, https://doi.org/10.1016/j.jhydrol.2023.129299, 2023.

Pinos, J., Latron, J., Levia, D. F., and Llorens, P.: Drivers of the circumferential variation of stemflow inputs on the boles of *Pinus sylvestris* L. (Scots pine), Ecohydrology, 14(8), e2348, https://doi.org/10.1002/eco.2348, 2021.

Ponette-González, A.G., Weathers, K.C., and Curran, L.M.: Water inputs across a tropical montane landscape in Veracruz, Mexico: synergistic effects of land cover, rain and fog seasonality, and interannual precipitation variability, Global Change Biol., 16(3), 946–963, https://doi.org/10.1111/j.1365-2486.2009.01985.x, 2010.

Price, A.G., Dunham, K., Carleton, T., and Band, L.: Variability of water fluxes through the black spruce (*Picea mariana*) canopy and feather moss (*Pleurozium schreberi*) carpet in the boreal forest of Northern Manitoba, J. Hydrol., 196(1–4), 310–323, https://doi.org/10.1016/S0022-1694(96)03233-7, 1997.

Reynaert, S., De Boeck, H.J., Verbruggen, E., Verlinden, M., Flowers, N., and Nijs, I.: Risk of short-term biodiversity loss under more persistent precipitation regimes, Global Change Biol., 27(8), 1614–1626, https://doi.org/10.1111/gcb.15501, 2021.

Rodrigues, A.F., Terra, M.C., Mantovani, V.A., Cordeiro, N.G., Ribeiro, J.P., Guo, L., Nehren, U., Mello, M.J., and Mello, C.R.: Throughfall spatial variability in a neotropical forest: Have we correctly accounted for time stability?, J. Hydrol., 608, 127632, https://doi.org/10.1016/j.jhydrol.2022.127632, 2022.

Seiler, J., and Matzner, E.: Spatial variability of throughfall chemistry and selected soil properties as influenced by stem distance in a mature Norway spruce (*Picea abies*, Karst.) stand, Plant Soil, 176, 139–147, https://doi.org/10.1007/BF00017684, 1995.

Shen, W.J., Ren, H.L., Jenerette, G.D., Hui, D.F., and Ren, H.: Atmospheric deposition and canopy exchange of anions and cations in two plantation forests under acid rain influence, Atmos Environ., 64, 242–250, https://doi.org/10.1016/j.atmosenv.2012.10.015, 2013.

Shinohara, Y., Levia, D.F., Komatsu, H., Nogata, M., and Otsuki, K.: Comparative modeling of the effects of intensive thinning on canopy interception loss in a Japanese cedar (*Cryptomeria japonica* D. Don) forest of western Japan, Agric. For. Meteorol., 214–215, 148–156, https://doi.org/10.1016/j.agrformet.2015.08.257, 2015.

Siegert, C.M., and Levia, D.F.: Seasonal and meteorological effects on differential stemflow funneling ratios for two deciduous tree species, J. Hydrol., 519, 446–454, https://doi.org/10.1016/j.jhydrol.2014.07.038, 2014.

Staelens, J., De Schrijver, A., and Verheyen, K.: Seasonal variation in throughfall and stemflow chemistry beneath a European beech (*Fagus sylvatica*) tree in relation to canopy phenology, Can. J. Forest Res., 37(8), 1359–1372, https://doi.org/10.1139/X07-003, 2007.

Staelens, J., De Schrijver, A., Verheyen, K., and Verhoest, N.E.: Spatial variability and temporal stability of throughfall deposition under beech (*Fagus sylvatica* L.) in relationship to canopy structure, Environ. Pollut., 142(2), 254–263, https://doi.org/10.1016/j.envpol.2005.10.002, 2006.

Su, L., Zhao, C.M., Xu, W.T., and Xie, Z.Q.: Hydrochemical fluxes in bulk precipitation, throughfall, and stemflow in a mixed evergreen and deciduous broadleaved forest, Forests, 10(6), 507, https://doi.org/10.3390/f10060507, 2019.

Sun, J.M., Yu, X.X., Wang, H.N., Jia, G.D., Zhao, Y., Tu, Z.H., Deng, W.P., Jia, J.B., and Chen, J.G. Effects of forest structure on hydrological processes in China, J. Hydrol., 561, 187–199, https://doi.org/10.1016/j.jhydrol.2018.04.003, 2018.

Sun, S.Y., Liu, X.F., Lu, S.X., Cao, P.L., Hui, D.F., Chen, J., Guo, J.F., and Yang, Y.S.: Depth-dependent response of particulate and mineral-associated organic carbon to long-term throughfall reduction in a subtropical natural forest, Catena, 223, 106904, https://doi.org/10.1016/j.catena.2022.106904, 2023.

Tonello, K.C., Rosa, A.G., Pereira, L.C., Matus, G.N., Guandique, M.E.G., and Navarrete, A.A.: Rainfall partitioning in the Cerrado and its influence on net rainfall nutrient fluxes, Agric. For. Meteorol., 303, 108372, https://doi.org/10.1016/j.agrformet.2021.108372, 2021a.

Tonello, K.C., Van Stan II, J.T., Rosa, A.G., Balbinot, L., Pereira, L.C., and Bramorski, J.: Stemflow variability across tree stem and canopy traits in the Brazilian Cerrado, Agric. For. Meteorol., 308, 108551, https://doi.org/10.1016/j.agrformet.2021.108551, 2021b.

Turpault, M.P., Kirchen, G., Calvaruso, C., Redon, P.O., and Dincher, M.: Exchanges of major elements in a deciduous forest canopy, Biogeochemistry, 152, 51–71, https://doi.org/10.1007/s10533-020-00732-0, 2021.

Wu, T., Song, Y.T, Tissue, D., Su, W., Luo, H.Y, Li, X., Yang, S.M., Liu, X.J., Yan J.H., Huang, J., and Liu, J.X.: Photosynthetic and biochemical responses of four subtropical tree seedlings to reduced dry season and increased wet season precipitation and variable N deposition, Tree Physiol., 44(1), tpad114, https://doi.org/10.1093/treephys/tpad114, 2023.

Wu, Y.P., Yin, X.W., Zhou, G.Y., Bruijnzeel, L. A., Dai, A.G., Wang, F., Gentine, P., Zhang, G.C., Song, Y.N., and Zhou, D.C.: Rising rainfall intensity induces spatially divergent hydrological changes within a large river basin, Nat. Commun., 15(1), 823, https://doi.org/10.1038/s41467-023-44562-8, 2024.

Van Stan II, J.T., and Pypker, T.G.: A review and evaluation of forest canopy epiphyte roles in the partitioning and chemical alteration of precipitation, Sci. Total Environ., 536, 813–824, https://doi.org/10.1016/j.scitotenv.2015.07.134, 2015.

Van Stan, J.T., Wagner, S., Guillemette, F., Whitetree, A., Lewis, J., Silva, L., and Stubbins, A.: Temporal dynamics in the concentration, flux, and optical properties of tree-derived dissolved organic matter in an epiphyte-laden oak-cedar forest, J. Geophys. Res-Biogeo., 122(11), 2982–2997. https://doi.org/10.1002/2017JG004111, 2017.

Wang, C.Y., Sun, X.C., Fan, C.B., Wei, Y.X., Jia, G.K., and Cao, Y.H.: Spatio-temporal variability and intra-event variation of throughfall ammonium and nitrate in a pine plantation, Hydrol. Process., 37, e14872, https://doi.org/10.1002/hyp.14872, 2023.

Yan, J.H., Zhou, G.Y., Zhang, D.Q., and Wang, X.: Spatial and temporal variations of some hydrological factors in a climax forest ecosystem in the Dinghushan region, Acta Ecol. Sin., 23(11), 2359–2366, https://europepmc.org/article/cba/534217, 2003.

Yue, K., De Frenne, P., Fornara, D.A., Van Meerbeek, K., Li, W., Peng, X., Ni, X.Y., Peng, Y., Wu, F.Z., Yang Y.S., and Peñuelas, J.: Global patterns and drivers of rainfall partitioning by trees and shrubs, Global Change Biol., 27(14), 3350–3357, https://doi.org/10.1111/gcb.15644, 2021.

Zabret, K., Rakovec, J., and Šraj, M.: Influence of meteorological variables on rainfall partitioning for deciduous and coniferous tree species in urban area, J. Hydrol., 558, 29–41, https://doi.org/10.1016/j.jhydrol.2018.01.025, 2018.

Zhang, W.J., Zhu, X.A., Chen, C.F., Zeng, H.H., Jiang, X.J., Wu, J.E., Zou, X., Yang, B., and Liu, W.J.: Large broad-leaved canopy of banana (*Musa nana* Lour.) induces dramatically high spatial–temporal variability of throughfall, Hydrol. Res., 52(6), 1223–1238, https://doi.org/10.2166/nh.2021.023, 2021.

Zhang, Y.F., Wang, X.P., Hu, R., Pan, Y.X., and Paradeloc, M.: Rainfall partitioning into throughfall, stemflow and interception loss by two xerophytic shrubs within a rain-fed re-vegetated desert ecosystem, northwestern China, J. Hydrol., 527, 1084–1095, https://doi.org/10.1016/j.jhydrol.2015.05.060, 2015.

Zhang, Y.F., Yuan, C., Chen, N., and Levia, D.F.: Rainfall partitioning by vegetation in China: A quantitative synthesis, J. Hydrol. 617, 128946, https://doi.org/10.1016/j.jhydrol.2022.128946, 2023.

Zhao, W.Y., Ji, X.B., Jin, B.W., Du, Z.Y., Zhang, J.L., Jiao, D.D., and Zhao, L.W.: Experimental partitioning of rainfall into throughfall, stemflow and interception loss by *Haloxylon ammodendron*, a dominant sand-stabilizing shrub in northwestern China, Sci. Total Environ., 858, 159928, https://doi.org/10.1016/j.scitotenv.2022.159928, 2023.

Zheng, M.H., Zhang, T., Luo, Y.Q., Liu, J.X., Lu, X.K., Ye, Q., Wang, S.H., Huang, J., Mao, Q.G., Mo, J.M., and Zhang, W.: Temporal patterns of soil carbon emission in tropical forests under long-term nitrogen deposition, Nat. Geosci., 15, 1002–1010, https://doi.org/10.1038/s41561-022-01080-4, 2022.

Zhou, G.Y., Wei, X.H., Wu, Y.P., Liu, S.G., Huang, Y.H., Yan, J.H., Zhang, D.Q., Zhang, Q.M., Liu, J.X., Meng, Z., Wang, C.L., Chu, G.W., Liu, S.Z., Tang, X.L., and Liu, X.D.: Quantifying the hydrological responses to climate change in an intact forested small watershed in Southern China, Global Change Biol., 17(12), 3736–3746, https://doi.org/10.1111/j.1365-2486.2011.02499.x, 2011.

Ziegler, A.D., Giambelluca, T.W., Nullet, M.A., Sutherland, R.A., Tantasarin, C., Vogler, J.B., and Negishi, J.N.: Throughfall in an evergreen-dominated forest stand in Northern Thailand: comparison of mobile and stationary methods, Agric. For. Meteorol., 149, 373–384, https://doi.org/10.1016/j.agrformet.2008.09.002, 2009.

Zimmermann, A., Wilcke, W., and Elsenbeer, H.: Spatial and temporal patterns of throughfall quantity and quality in a tropical montane forest in Ecuador, J. hydrol., 343(1–2), 80–96, https://doi.org/10.1016/j.jhydrol.2007.06.012, 2007.

Tables

Table 1. Correlations between throughfall and stemflow and rainfall and forest factors

	Gross rainfall	DBH	CA	Height	LAI
Throughfall	0.72^{***}	—	—	—	-0.58^{**}
stemflow	0.77^{***}	0.65^{*}	-0.75^{**}	0.54^{**}	-0.55^{**}

DBH: diameter at breast height; CA: crown area; LAI: leaf area index. $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$

Table 2. Analysis of variance (ANOVA) for throughfall and stemflow affected by rainfall classifications and tree species

Summary of ANOVA	Throughfall		Stemflow
Rainfall classification (R)	< 0.05	Rainfall classification (R)	< 0.001
Forest type (F)	< 0.001	Tree species (T)	< 0.001
R × F	0.861	R × T	< 0.001

$\alpha = 0.05$

Figures

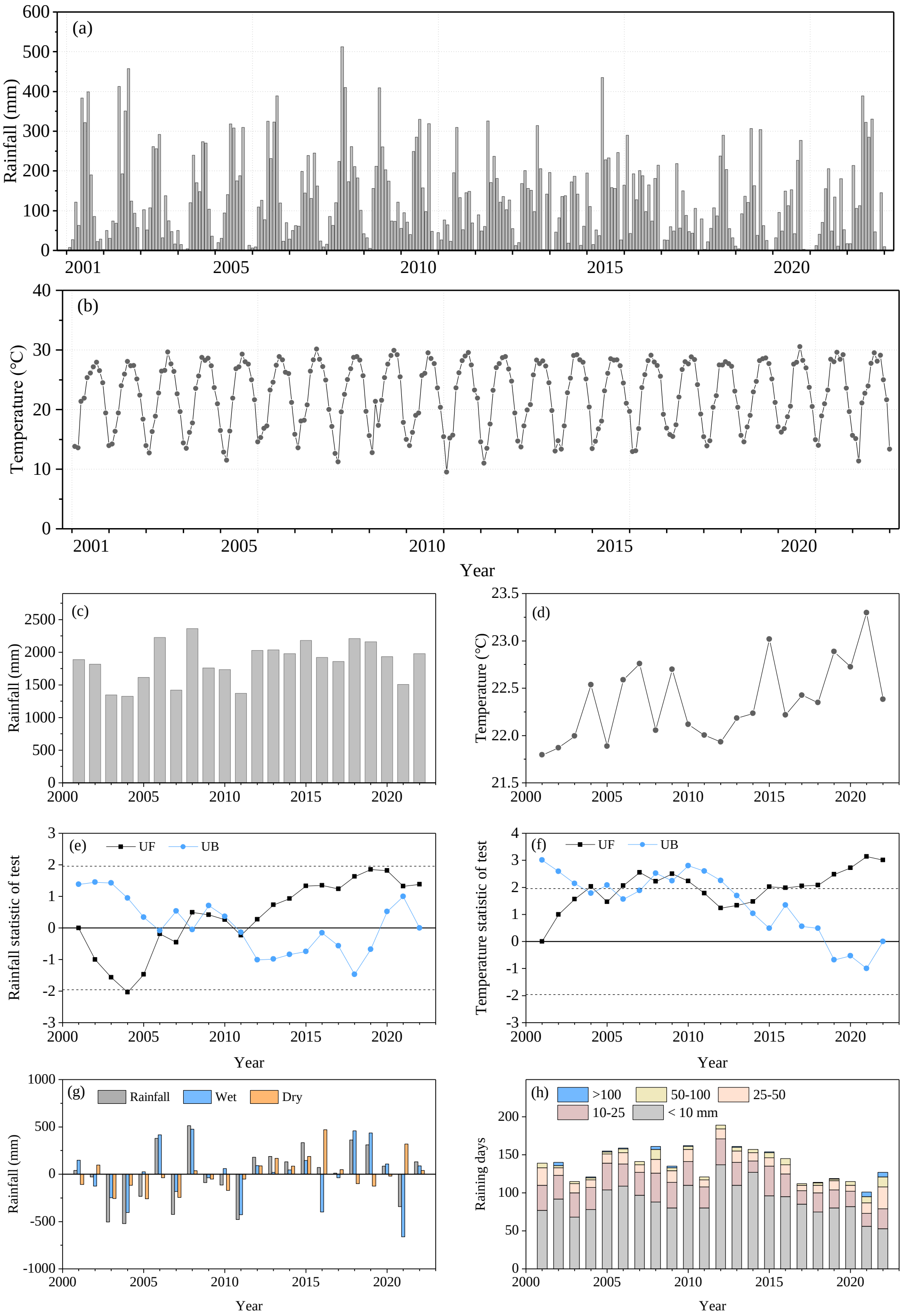

Figure 1. (a) and (b) rainfall and temperature in Dinghushan Biosphere Reserve in Southern China from 2001–2022, (c) and (d) annual rainfall and temperature, (e) and (f) rainfall and temperature statistic of Mann-Kendall test, respectively. (g) Anomaly of annual rainfall from 2001–2022, (h) annual raining days in five classifications. UF (Unadjusted Forward) > 0 indicate a continuous increasing trend (*P* < 0.05). The intersection points of UF and UB (Unadjusted Backward) is the mutation time point. Within the confidence interval [-1.96, 1.96], the variable presents a significantly mutation growth state at this time point (*P* < 0.05).

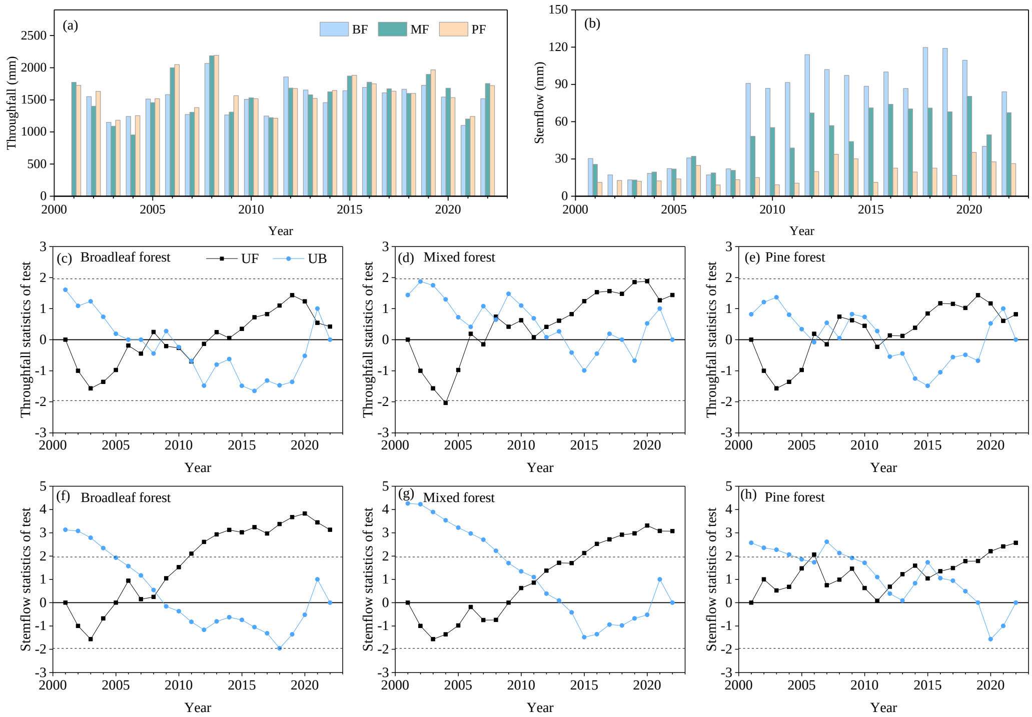

Figure 2. (a) and (b) Annual throughfall and stemflow in the broadleaf forest (BF), mixed pine and broadleaf forest (MF) and pine forest (PF) from 2001–2022, respectively, (c) ~ (h) rainfall and stemflow statistic of Mann-Kendall test, respectively. UF (Unadjusted Forward) > 0 indicate a continuous increasing trend (P < 0.05). The intersection points of UF and UB (Unadjusted Backward) is the mutation time point. Within the confidence interval [-1.96, 1.96], the variable presents a significantly mutation growth state at this time point (P < 0.05).

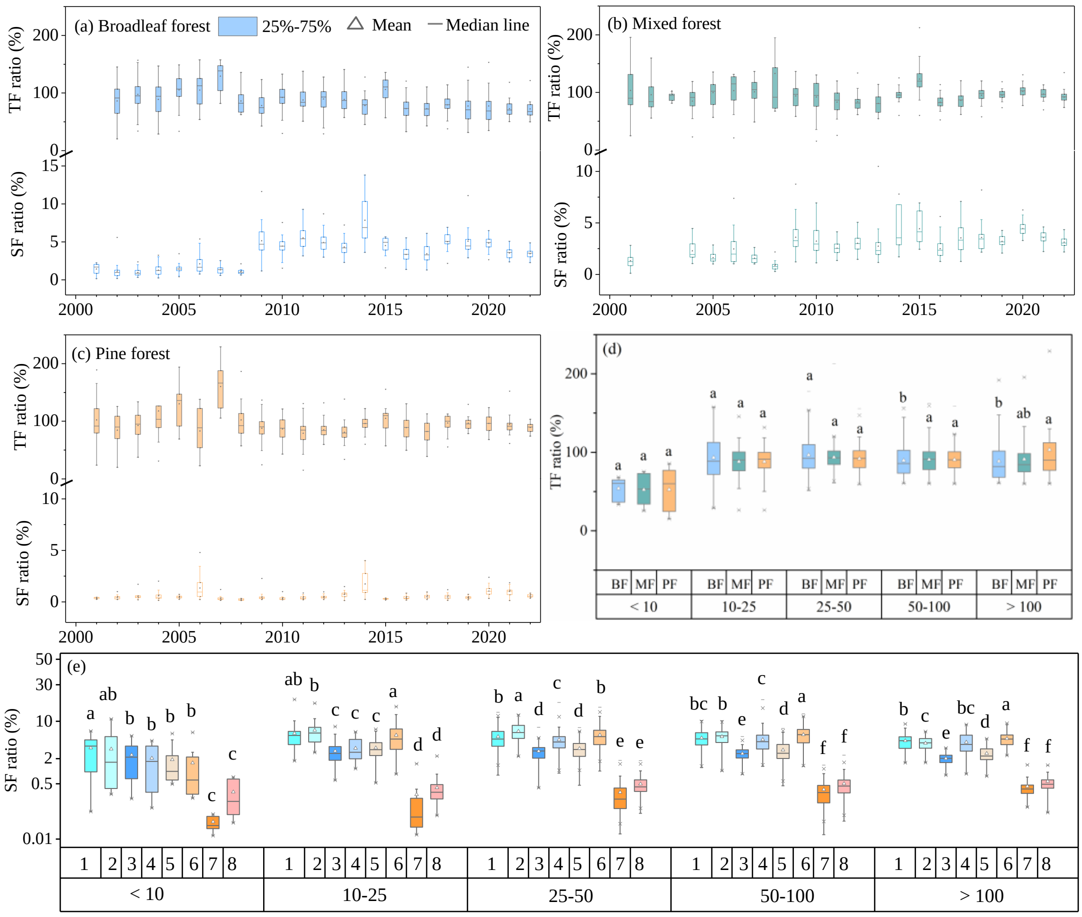

Figure 3. Box plots of throughfall ratio and stemflow ratio in (a) broadleaf forest, (b) mixed pine and broadleaf forest and (c) pine forest from 2001–2022. Boxed plots of (d) TF ratio in the three forests and (e) SF ratio for eight plant species based on the rainfall classifications (broadleaf forest: *Acmena acuminatissima* (Blume) Merr. et Perry (SF1), *Cryptocarya chinensis* (Hance) Hemsl. (SF2), *Gironniera subaequalis* Planch. (SF3), *Schima superba* Gardn. et Champ. (SF4); mixed forest: *Castanea henryi* (Skam) Rehd. et Wils. (SF5), *Schima superba* Gardn. et Champ. (SF6), *Pinus massoniana* Lamb. (SF7); pine forest: *Pinus massoniana* Lamb. (SF8). Different letters indicate a significant difference at $P < 0.05$

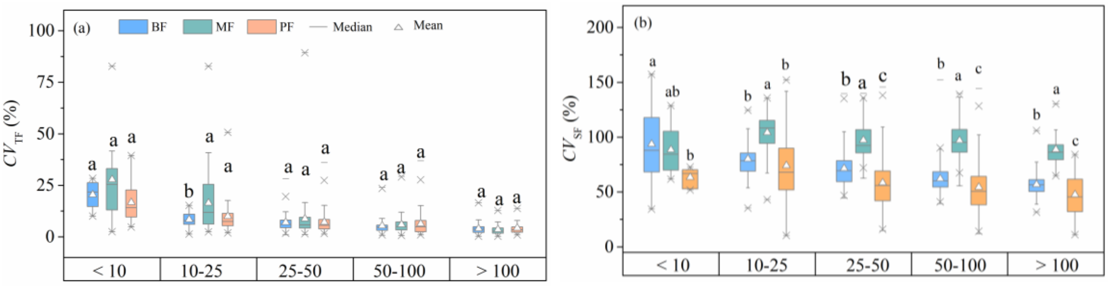

Figure 4. Box plots of coefficient of variation (*CV*, %) in (a) throughfall (TF) and (b) stemflow (SF) in broadleaf forest (BF), mixed pine and broadleaf forest (MF) and pine forest (PF) based on the rainfall classifications. Different letters indicate a significant difference at $P < 0.05$

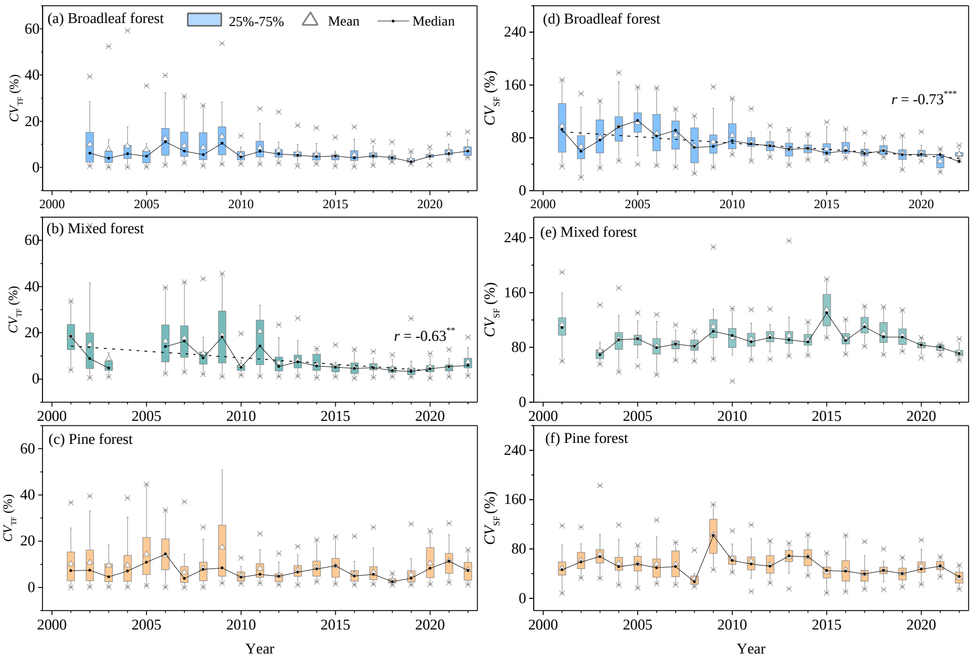

Figure 5. Box plots of coefficient of variation (*CV*, %) in (a, b, and c) throughfall (TF) and (d, e, and f) stemflow (SF) in the three forests from 2001 to 2022. Medians of annual *CV* were fitted. *r*: Pearson coefficient of correlation; *: $P < 0.05$, **: $P < 0.01$, ***: $P < 0.001$

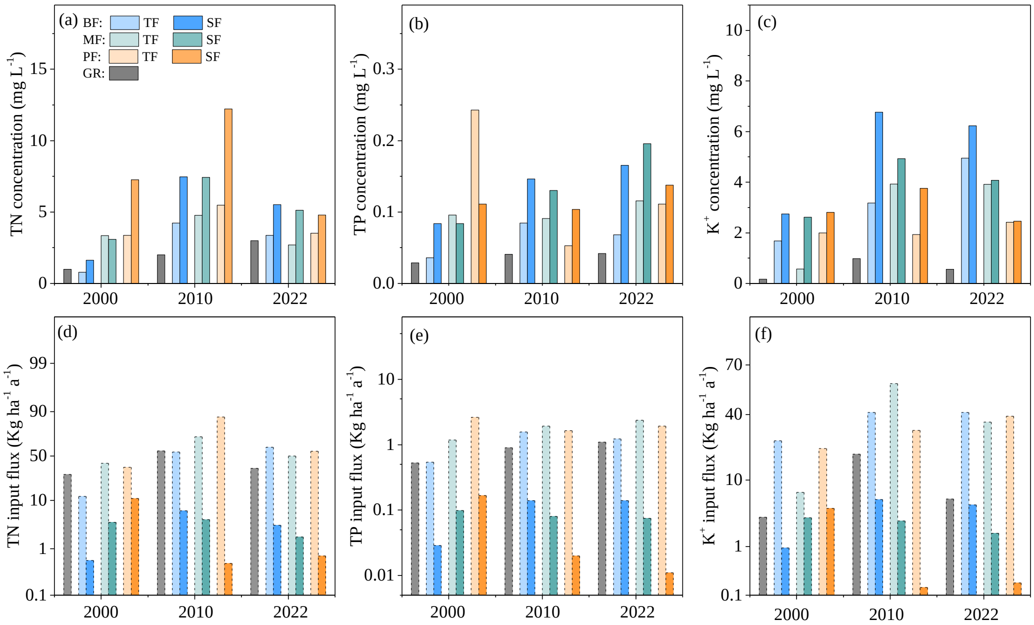

Figure 6. Concentrations and fluxes of TN, TP and K^{+} of gross rainfall (GR), throughfall (TF) and stemflow (SF) in the broadleaf forest (BF), mixed forest (MF) and pine forest (PF) in 2000, 2010 and 2022, respectively.

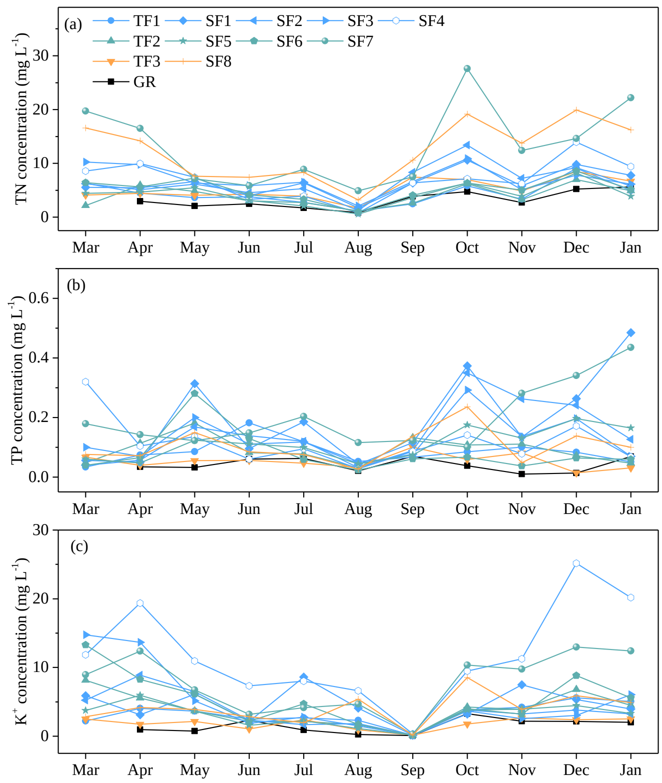

Figure 7. Monthly concentrations of (a) TN, (b) TP and (c) K^+ of throughfall (TF1) and stemflow (SF1, SF2, SF3 and SF4) in the broadleaf forest, throughfall (TF2) and stemflow (SF5, SF6 and SF7) in the mixed forest, throughfall (TF3) and stemflow (SF8) in the pine forest.

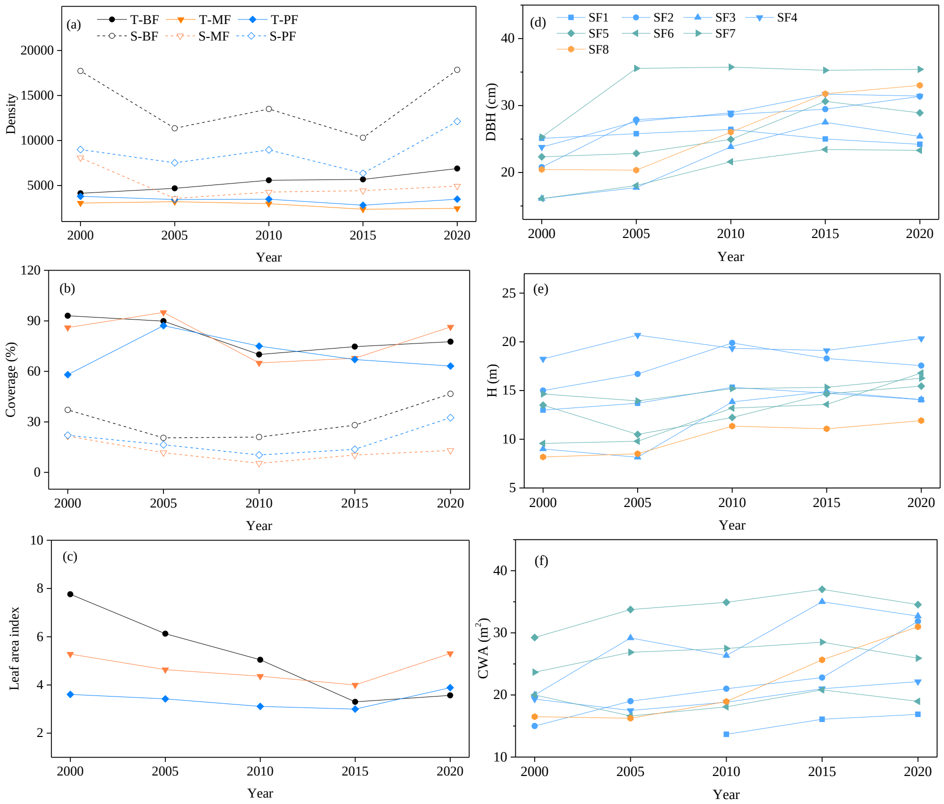

Figure 8. Plant density, canopy coverage and leaf area index of tree (T) and shrub (S) in the broadleaf forest (BF), mixed forest (MF) and pine forest (PF), respectively. Diameter at breast height (DBH), height (H) and crown area (CA) is given for eight stemflow-sampled trees, respectively. Tree height was measured using laser range finder. Tape measure was used to measure the diameter of trees at a height of 1.3 m, namely DBH (diameter at breast height). CA (crown area): the laser rangefinder was used to measure the maximum diameter at the edge of the canopy, with multiple measurements at different points to ensure accuracy. Plant density: 25 plots of 20 m × 20 m (A1-A25 plots) were built on a plot of 1hm^2 to survey tree density. Then, 25 plots of 5 m × 5 m (B1-B25 plots) were randomly set on the A1-A25 plots to survey shrub density. Finally, 25 plots of 1 m × 1 m (C1-C25 plots) were randomly set on the B1-B25 plots to survey herb density. Canopy coverage: 25 observation plots (1 m × 1 m) were selected in the 1 hm^2 area of each forest type. The percentage of the surface area covered by plants to the total plot area is termed canopy coverage (%). LAI (Leaf area index) was measured using a LAI-2200 plant canopy analyzer with 90° view caps (Li-Cor Inc., USA). 10 observation points (distance about 10 m) were selected in the 1 hm^2 area of each forest type with 5 replications.